"Robust Exploration and Commercial Missions to the Moon Using NTR / LANTR Propulsion and Lunar-Derived Propellants"

"Propelling Us to New Worlds"

Session 3G: Infrastructure and Capabilities

Stanley K. Borowski, Stephen W. Ryan, Laura M. Burke (NASA/GRC)
David R. McCurdy, James E. Fittje (Vantage Partners, LLC at GRC)
Claude R. Joyner (Aerojet Rocketdyne)
216-977-7091, Stanley.K.Borowski@nasa.gov

presented at the

Nuclear and Emerging Technologies for Space (NETS)-2017 Conference
Orlando, FL

Wednesday, March 1, 2017

Background Information and Presentation Overview

• NASA's current focus is on the *"Journey to Mars"* sometime around the mid-to-late 2030's. However, it is also supporting the development of commercial cargo and crew delivery to the ISS (e.g., Space*X*, Orbital Sciences, SNC, Boeing) where inflatable habitation technology (e.g., Bigelow Aerospace's BEAM) is currently being tested

• Significant private sector interest in commercial lunar activities has also been expressed by Bigelow Aerospace, Golden Spike Company, Shackleton Energy Company (SEC), and most recently by United Launch Alliance (ULA) in their "Cislunar-1000" plan

• Lunar-derived propellant (LDP) production – specifically LLO_2 and LLH_2 – offers significant mission leverage and are central themes of both SEC's and ULA's plans for commercial lunar development

• An efficient, proven propulsion technology with reuse capability – like NTP – offers the potential for affordable "*access through space*" essential to realizing commercial lunar missions

• ***Question***: *How can high performance NTP and the leverage potential of LDP best be exploited?*
Answer: *"LO_2-Augmented" NTR (LANTR) – LH_2-cooled NTR with "O_2-afterburner" nozzle combines NTR and supersonic combustion ramjet engine technologies allowing "bipropellant" engine operation*

• This presentation examines the performance potential of an "evolutionary" lunar transportation system (LTS) architecture using NTR initially, then transitioning to LANTR as LDP's (e.g., LLO_2 from regolith or volcanic glass, LLO_2 and LLH_2 from lunar polar ice deposits) become available in lunar orbit (LO)

• Mission applications range from cargo delivery, to crewed landing, to routine commuter flights to and from transportation system nodes located in both lunar equatorial and lunar polar orbits

Benefits and Options for Using Lunar-Derived Propellants

- Studies conducted by NASA and its contractors (early 1980's – early 1990's) indicated a substantial benefit from using lunar-derived propellants – specifically lunar-derived LO_2 (LLO_2) or "*LUNOX*" in a lunar space transportation system (LTS)

- With a LTS using LO_2/LH_2 chemical rockets, ~6 kilograms (kg) of mass in low Earth orbit (LEO) is required to place 1 kg of payload on the lunar surface (LS)

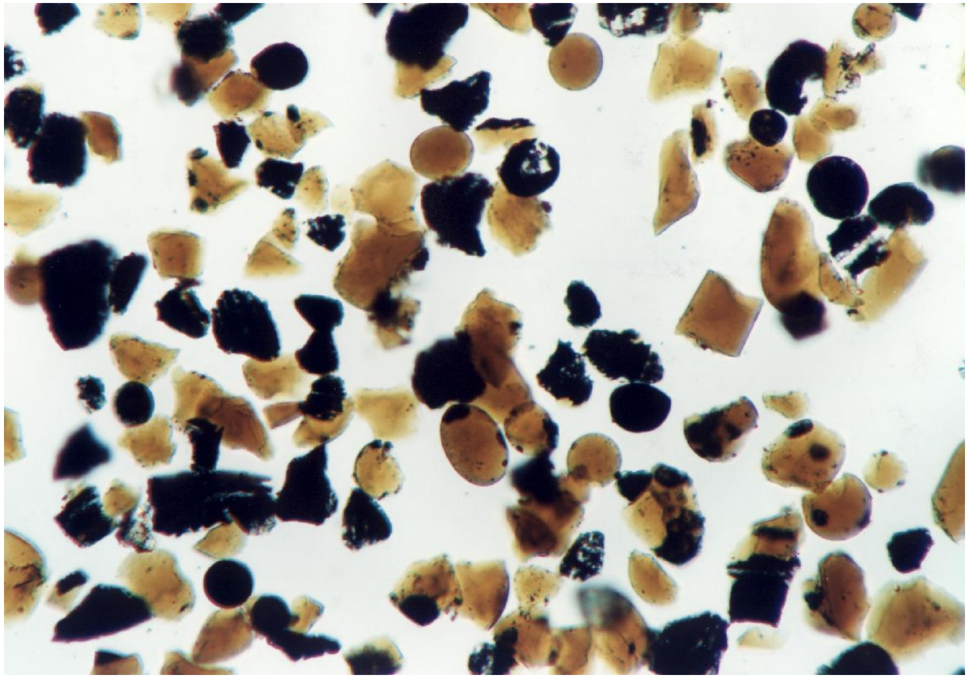
- Of this 6 kg, ~70% (4.2 kg) is propellant and 6/7th of this mass (3.6 kg) is oxygen assuming an O/H MR = 6:1

- Since the cost of placing a kilogram of mass on the LS is ~6X the cost of delivering it to LEO, the ability to produce and utilize LUNOX or lunar-derived LO_2 and hydrogen (LLH_2) from lunar polar ice deposits can provide significant mission leverage

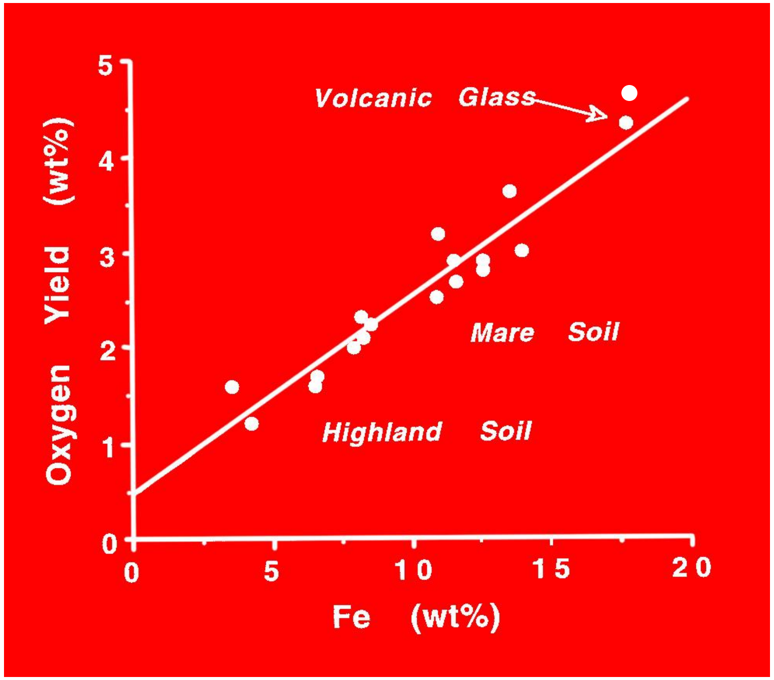
- Providing LUNOX for use in fuel cells, life support systems and LO_2/LH_2 chemical rockets used on lunar landing vehicles (LLVs), can allow "high value" cargo (people, manufacturing and scientific equipment, etc.) to be transported to LEO, then to the Moon instead of bulk LO_2 propellant

- Oxygen is abundant in the lunar regolith (~43% by mass) and can be extracted using a variety of techniques, such as hydrogen reduction of "ilmenite ($FeOTiO_2$)" or "FeO-rich" volcanic glass ("orange soil") discovered during the Apollo 17 mission to Taurus-Littrow

Volcanic Glass from the Apollo 17 Mission to Taurus-Littrow is Attractive for LUNOX Production



The best lunar oxygen ore found during the Apollo Program is the volcanic glass, ("orange soil") found at Taurus-Littrow. The glass beads are ~40 mm in diameter. The orange beads are clear glass, while the black beads cooled at bit more slowly and had a chance to crystallize.



Oxygen yield is directly related to iron abundance for the full range of soil compositions. Highest yields are from " FeO-rich" volcanic glass.

Oxygen production from "FeO-rich" volcanic glass is a 2 step process:

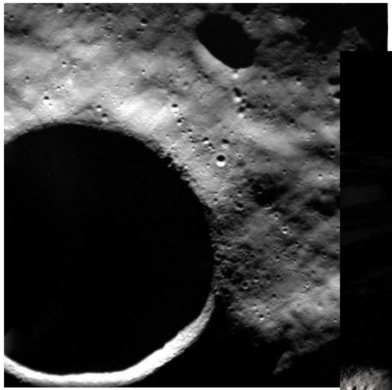
$FeO + H_2$ -------> $Fe + H_2O$	**$2\ H_2O$ -------> $2H_2 + O_2$ (*LUNOX*)**
(Hydrogen Reduction & Water Formation)	**(Water Electrolysis & Hydrogen Recycling)**

Ref: Carlton Allen, et al., "Oxygen extraction from lunar soils and pyroclastic glass", *J. Geophysical Research*, Vol. 101, No. E11, pgs. 26,085 – 26,095, Nov. 25, 1996

"Propelling Us to New Worlds"

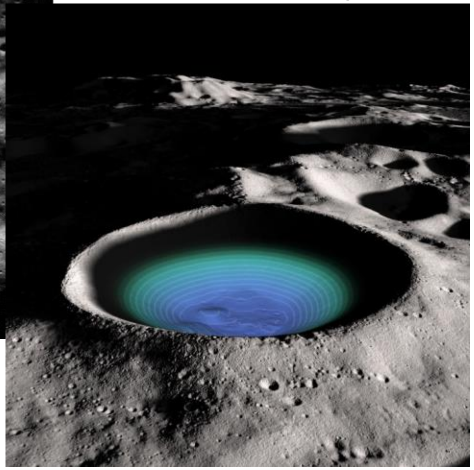
Extracting Water Ice from Permanently Shadowed Craters (Cold Traps) Found in the Moon's Polar Regions

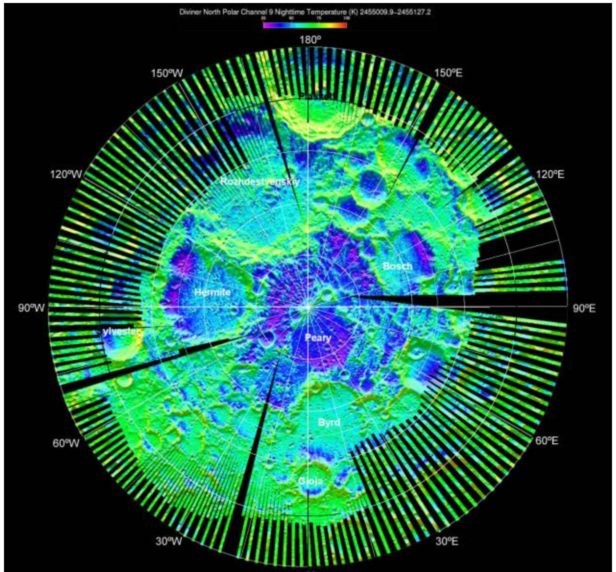
- Since the 1960's, scientists have conjectured that water ice could survive in the cold, permanently shadowed craters located at the Moon's poles
- The Clementine (1994), Lunar Prospector (1998), and Chandrayaan-1 (2008) lunar probes have provided data indicating the *possible* existence of large quantities of water ice (100's millions to billions of metric tons) at the lunar poles
- The Mini-SAR onboard Chandrayaan-1 discovered more than 40 permanently shadowed craters near the lunar north pole that are thought to contain ~600 million metric tons of water ice
- Lunar polar ice (LPI) deposits are important because they could supply both oxygen & hydrogen provided these deposits can be economically accessed, mined, processed and stored for their desired use
- Higher ΔV required to access LPO sites, candidate craters are deep and extremely cold (~50 K / -370 F) posing major mining challenges for mining and processing these cold materials (will probably need to warm material and equipment)
- LPI-derived water can then be electrolyzed on the Moon or in space (at an orbiting propellant depot)



Shackleton Crater at Lunar South Pole

Rim / Floor Dia ~21 km / 6.6 km, Depth ~4.2 km, 30 deg slope

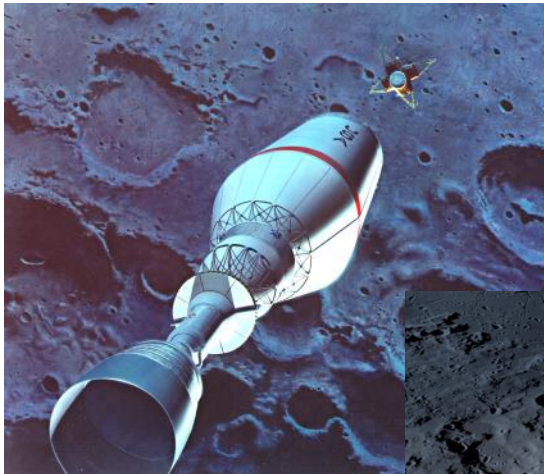




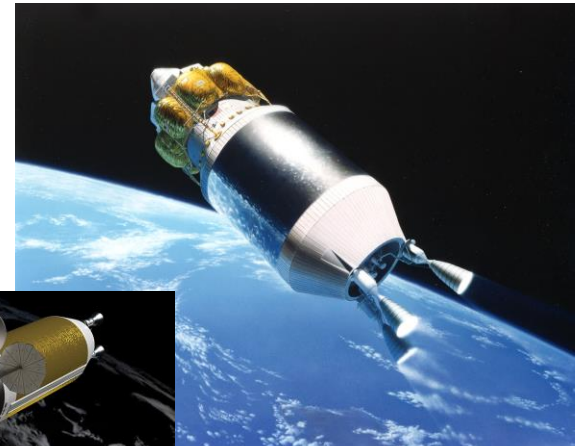
Lunar North Polar Region is Extremely Cold

Sampling of Crewed, Cargo & Commercial Lunar Transfer Vehicle Concepts Developed by GRC During the Past 25 Years

"Propelling Us to New Worlds"

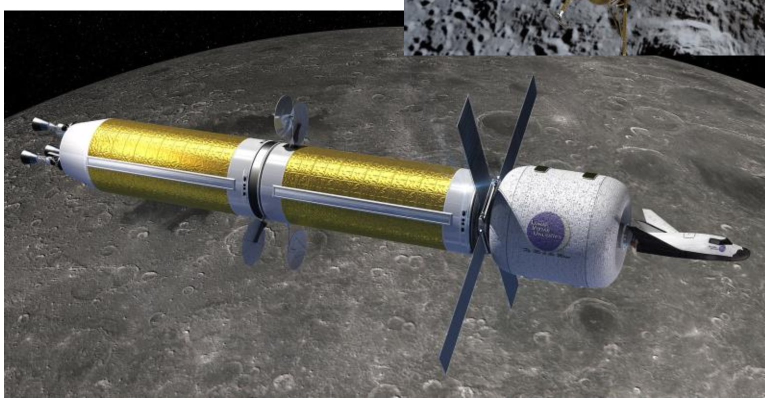


Expendable TLI Stage for "First Lunar Outpost" Mission uses 3 - 25 klb_f NTR Engines – Fast Track Study (1992)

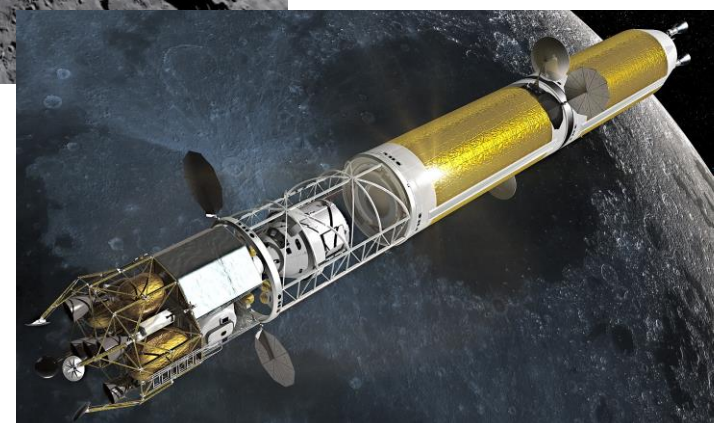


Reusable Lunar Transfer Vehicle uses Single 75 klb_f NTR Engine – SEI (1990 - 91)

Reusable Lunar Cargo Transport uses 3 – 16.7 klb_f "SNRE-class" Engines – (2013)



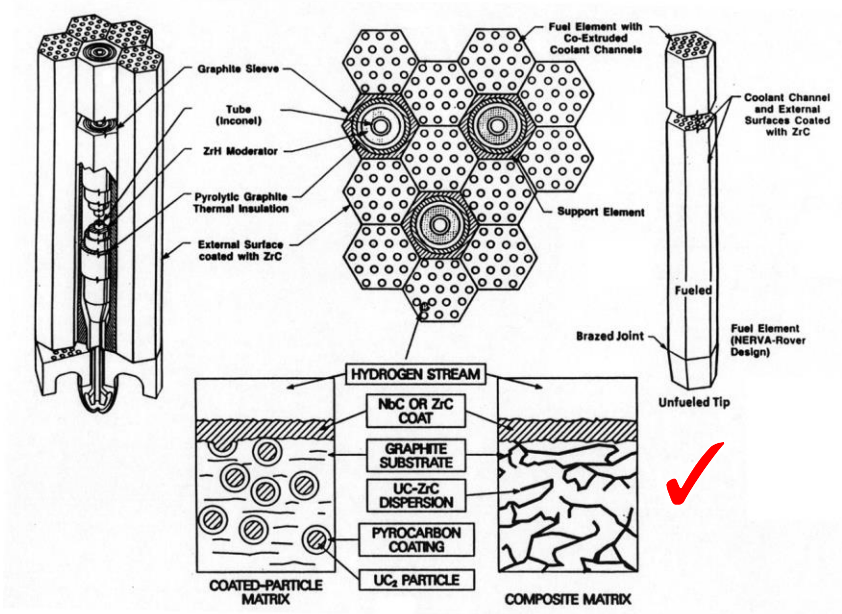
Commercial Tourism Polar Orbit Mission uses 3 – 16.7 klb_f "SNRE-class" Engines – (2013)

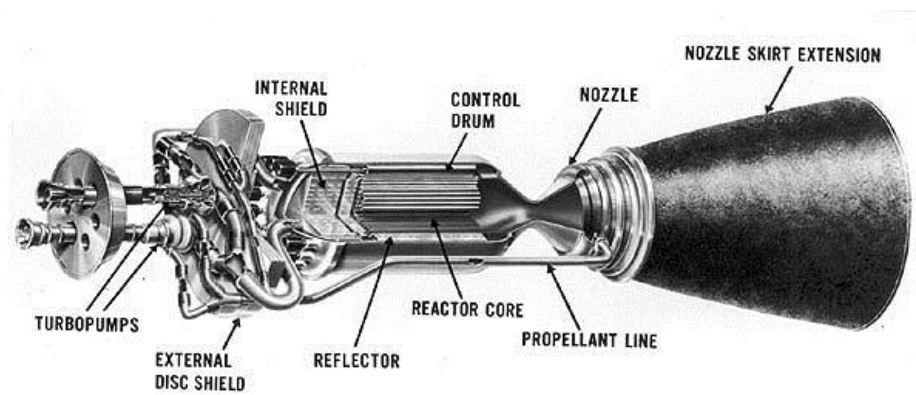


Reusable Crewed Landing Mission uses 3 – 16.7 klb_f "SNRE-class" Engines – (2013)

"Propelling Us to New Worlds"

"Heritage" Fuel Element (FE) / Tie Tube (TT) Arrangement / Performance Parameters for Small Nuclear Rocket Engine





Baseline Small Nuclear Rocket Engine (SNRE) Performance Parameters:

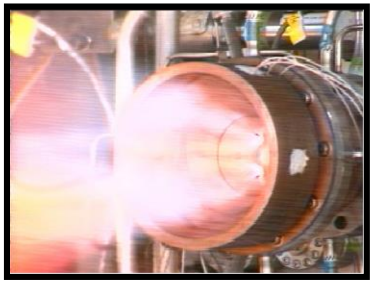
- Engine Cycle: **Expander**
- Thrust Level: **16.5 klb$_f$**
- Reactor Exit Temperature: **2734 K**
- Chamber Pressure: **1000 psia**
- Nozzle Area Ratio: **300:1**
- Specific Impulse (I_{sp}): **~900 s**
- Hydrogen Flow Rate: ~8.3 kg/s
- F / W_{eng} Ratio: **~3.03**
- Engine Length: ~5.8 m
- Nozzle Exit Diameter: ~1.53 m
- FE Length ~0.89 m (~35 inches)
- No. FEs / TTs: 564 / 241
- FE-to-TT Ratio: ~2:1
- Reactor Power Level: **~365 MWt**
- Fuel Matrix Power Density: ~3.44 MWt / liter
- U-235 Enrichment: **93%**
- Fuel Loading: ~0.6 grams / cm^3
- U-235 Inventory: ~60 kg

Ref: S. K. Borowski, et al., "Affordable Development and Demonstration of a Small NTR Engine: How Small is Big Enough?", AIAA-2015-4524; also as NASA/TM—2016-219402

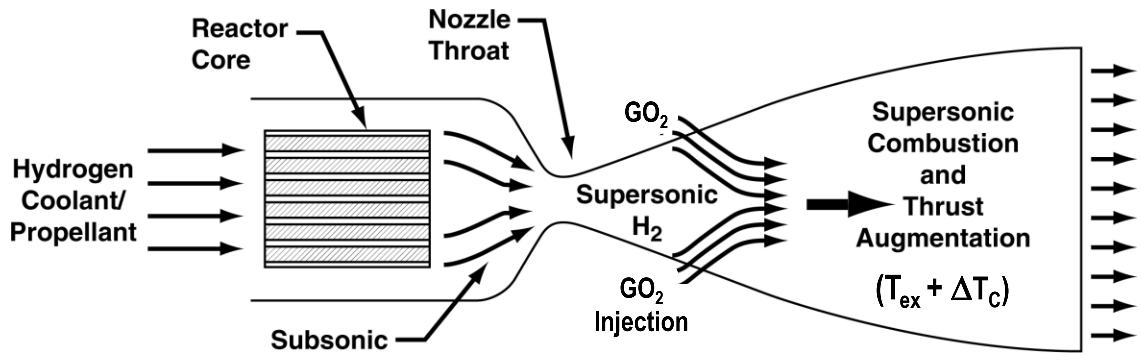
"LO_2-Augmented" NTR (LANTR) Concept: Operational Features and Performance Characteristics

"Propelling Us to New Worlds"

LANTR adds an O_2 "afterburner" nozzle and O_2-rich GG feed system to a conventional NTR engine that provides a variable thrust and Isp capability, shortens burn times, extends engine life, and allows bipropellant operation



Aerojet / GRC Non-Nuclear O_2 "Afterburner" Nozzle Test*



Hot H_2 Exhaust (T_{ex})

O/H Mixture Ratio	0	1	2	3	4	5
Delivered Isp (s)	900**	725	637	588	552	516
Thrust Augmentation Factor	1.0	1.611	2.123	2.616	3.066	3.441
Thrust (lb_f)	16,500	26,587	35,026	43,165	50,587	56,779
Engine Mass (lb_m)	5,462	5,677	5,834	5,987	6,139	6,295
Engine T/W	3.02	4.68	6.00	7.21	8.24	9.02

** Fuel Exit Temperature (T_{ex}) = 2734 K, Chamber Pressure = 1000 psia and NAR = 300 to 1

*Ref: M. J. Bulman and T. M. Neill, "Simulated LANTR Testing", AIAA 2000–3897

The Potential of LANTR Propulsion using Lunar-Derived Oxygen (LUNOX) was Analyzed by GRC more than 20 years ago!

"Propelling Us to New Worlds"

NASA/TM—1998-208830/REV2

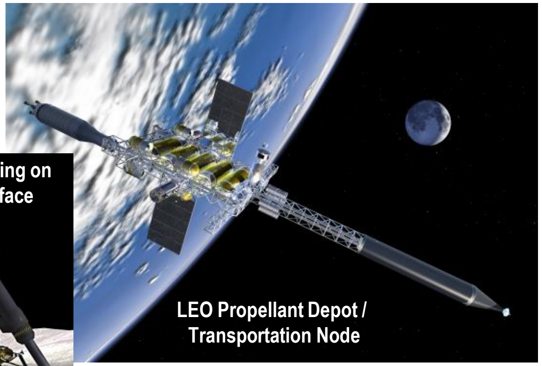
AIAA-1997-2956

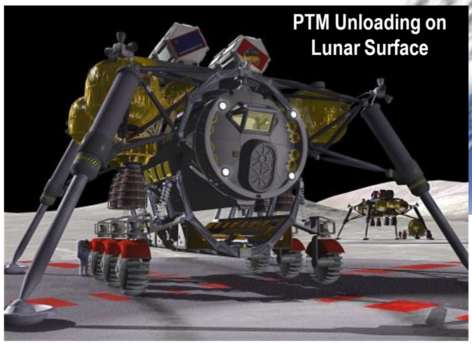
"2001: A Space Odyssey" Revisited—The Feasibility of 24 Hour Commuter Flights to the Moon Using NTR Propulsion with LUNOX Afterburners

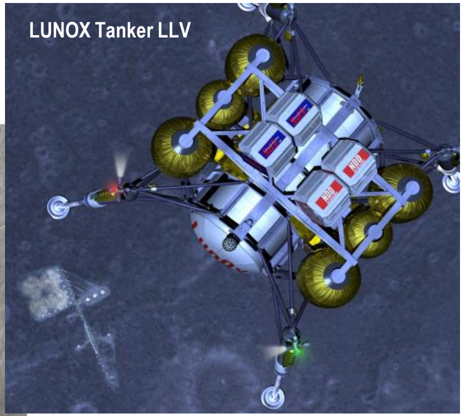
Stanley K. Borowski and Leonard A. Dudzinski
Glenn Research Center, Cleveland, Ohio

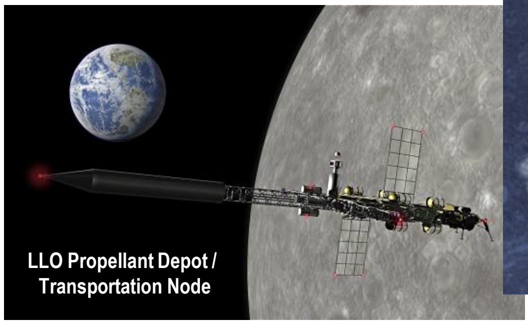
Presented at AIAA 33rd Joint Propulsion Conference
Seattle, Washington, July 6–9, 1997

- An evolutionary LTS was analyzed using conventional LH_2-cooled NTP initially then transitioning to LANTR
- "FeO-rich" volcanic glass beads from the Taurus-Littrow dark mantle deposit (DMD) was the source material for LUNOX production









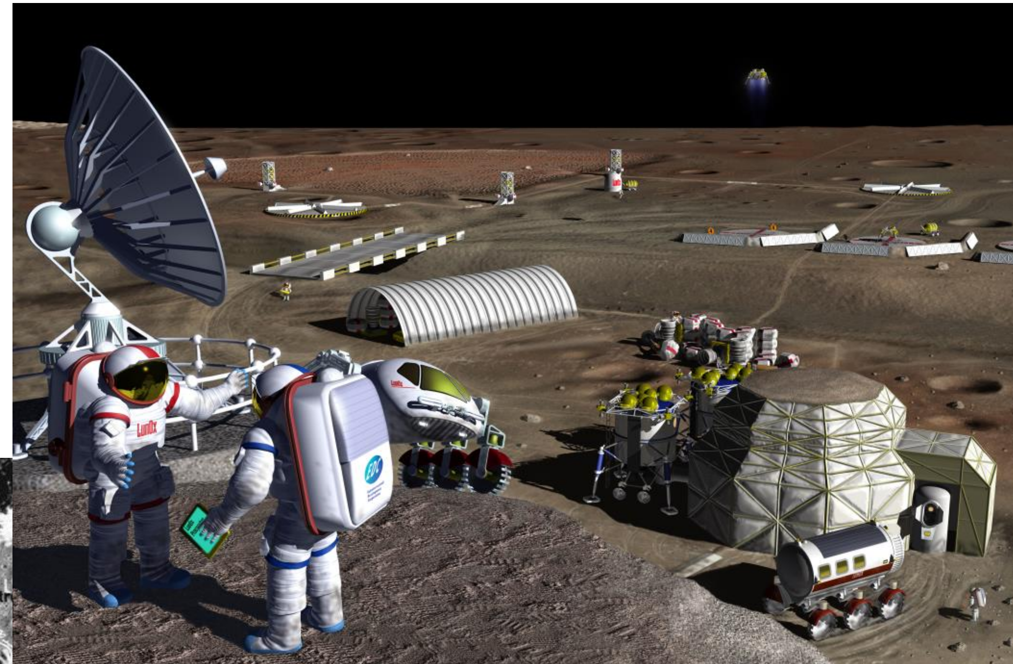
Images from "24 Hour Trips to the Moon using LANTR Propulsion" Animation by NASA GRC / SAIC

"Propelling Us to New Worlds"

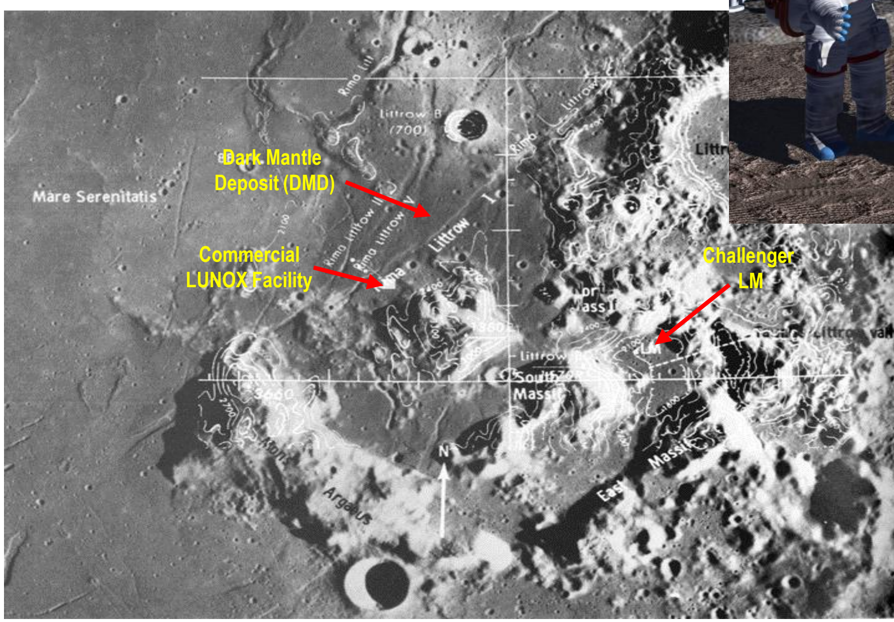
"Commercial" LUNOX Production Facility

Location: "Sea of Serenity" (Latitude: ~ 21° North / Longitude: ~29° East)

Vast deposits of "iron-rich" volcanic glass beads have been identified at a number of candidate sites on lunar near side (Sea of Serenity, Mare Vaporum, Rima Bode, and Sinus Aestuum) and the oxygen extraction process and efficiency using these DMD materials are known



Ref: S. K. Borowski, et al., "*2001: A Space Odyssey*" Revisited – The Feasibility of 24 Hour Commuter Flights to the Moon Using NTR Propulsion with LUNOX Afterburners", AIAA-1997-2956; also as NASA/TM—199802-208830 / Rev2



Index Map Showing the Apollo 17 Landing Site and Major Geographic Features of Taurus-Littrow Region

"Propelling Us to New Worlds"

Assumptions used in Analysis to Date

• An evolutionary LTS architecture is examined that uses a common NTPS with 3 – SNRE-class engines initially then transitions to LANTR engines and replaces in-line LH_2 tank with a LOX tank

• "1-way" transit times range from 72 – 24 hours are considered. Missions depart from LEO, capture into either lunar equatorial or polar orbits and then return to LEO (NOTE: Faster transit times preclude use of free return trajectory like that used in Apollo 13)

• LDP Options: (1) LUNOX production from "FeO-rich" volcanic glass or (2) LLOX and LLH_2 from LPI

• Initial LUNOX production goal focused on supporting surface-based LLV operation allowing LTVs to transport more high value cargo

• LANTR-powered LTVs use only Earth-supplied LH_2 (ELH_2) but refuel with LUNOX once it becomes available in LLO; O/H MR out and back was optimized to meet mission objectives and constraints

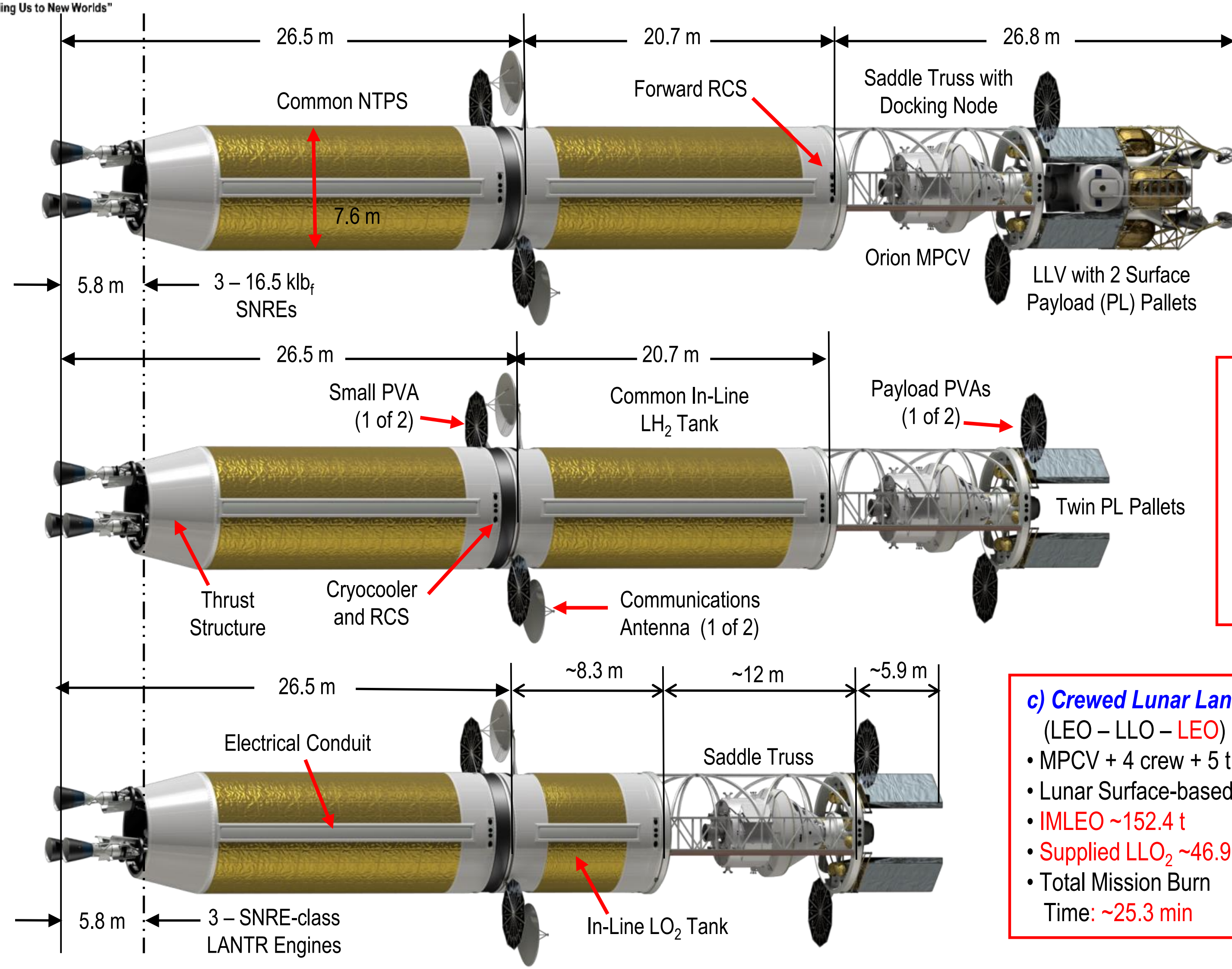
• LANTR LTVs also transport ELH_2 for use by the LLVs and for use in the hydrogen reduction process

• Eventually, a propellant depot in LLO is supplied with LUNOX from tanker LLVs and ELH_2 from either a dedicated NTR LH_2 "tanker" or LANTR LTV

• A propellant depot in LPO is supplied with H_2O from tanker LLVs; LANTR LTVs / commuter shuttles refuel with LLOX but are limited to using only excess LLH_2 from H_2O electrolysis for Earth return

NTR
"Propelling Us to New Worlds"

Variation in NLTV Size, IMLEO, Mission Capability and Burn Time Resulting from Use of LLO_2 and Transition to LANTR Engines



a) Crewed Lunar Landing:
(LEO – LLO – 24-hr EEO)
- 4 crew
- MPCV + LLV ~48 t
- IMLEO ~176.6 t
- Max Lift ~70 t (NTPS)
- Total Mission Burn Time: ~50 min

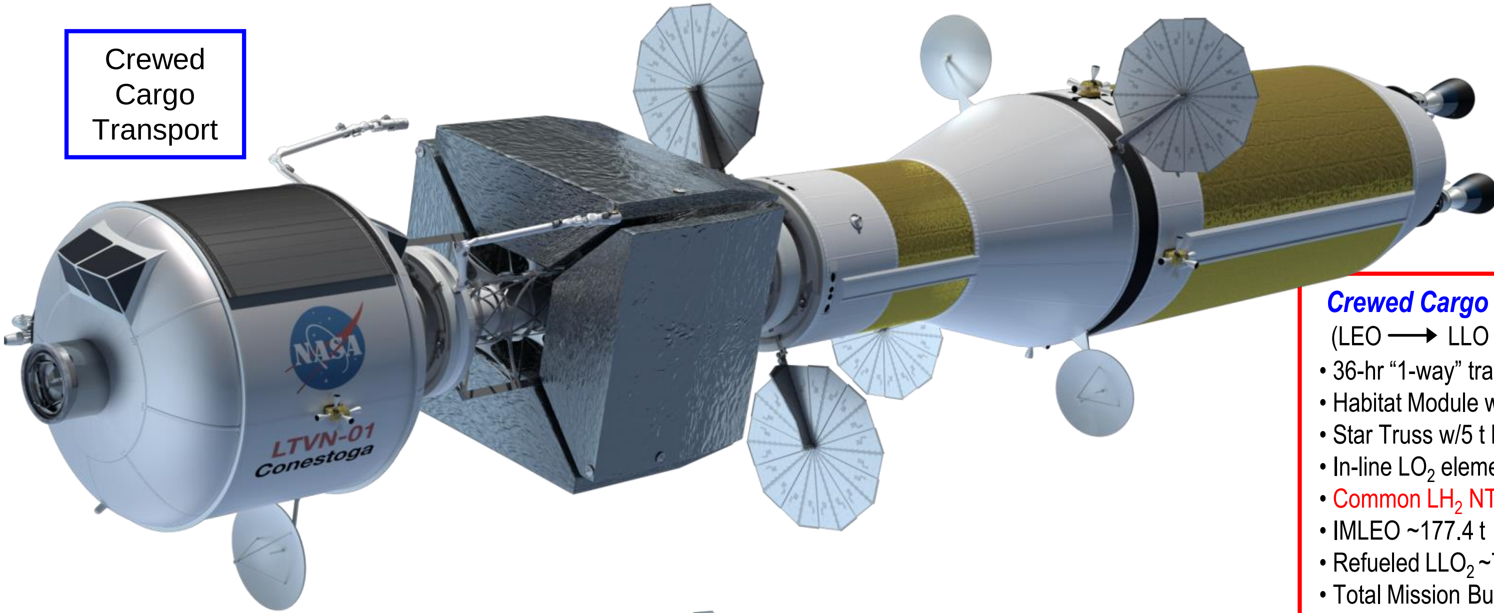
b) Crewed Lunar Landing:
(LEO – LLO – 3.25-hr EEO)
- MPCV + 4 crew + 5 t PL
- Lunar Surface-based LLV
- IMLEO ~146 t
- Max Lift ~70 t (NTPS)
- Total Mission Burn Time: ~50 min

c) Crewed Lunar Landing:
(LEO – LLO – LEO)
- MPCV + 4 crew + 5 t PL
- Lunar Surface-based LLV
- IMLEO ~152.4 t
- Supplied LLO_2 ~46.9 t
- Total Mission Burn Time: ~25.3 min

"Propelling Us to New Worlds"

Space-based LANTR LTVs using a Common LH_2 NTPS and Customized In-Line LO_2 Tank Element

Crewed Cargo Transport

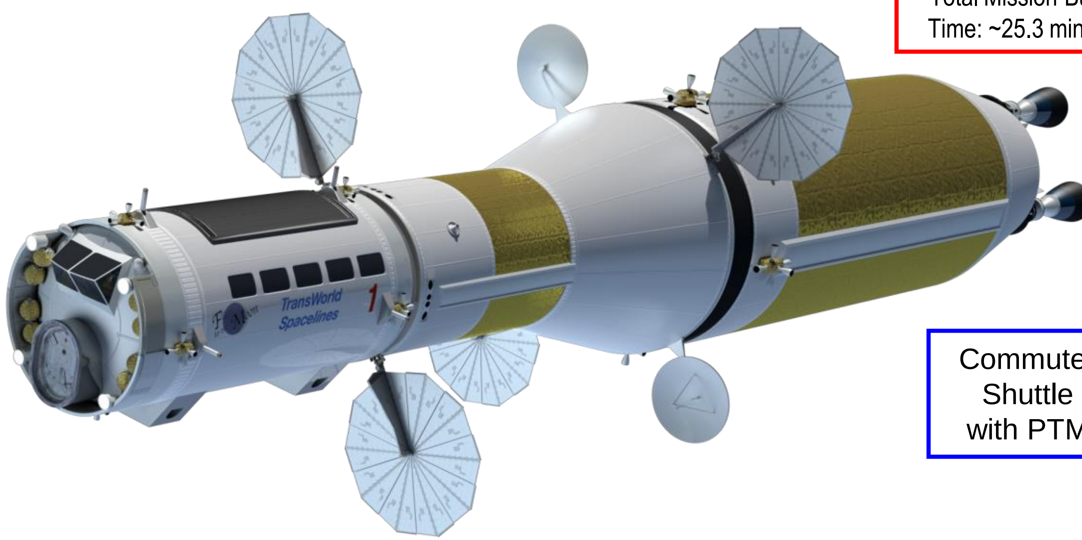


Case #4

Crewed Cargo Transport:
(LEO ⟶ LLO ⟶ LEO)
- 36-hr "1-way" transit times
- Habitat Module w/4 crew ~11.2 t
- Star Truss w/5 t Payload ~8.6 t
- In-line LO_2 element ~86.6 t
- Common LH_2 NTPS ~ 70.9 t
- IMLEO ~177.4 t
- Refueled LLO_2 ~71.6 t
- Total Mission Burn Time: ~25.3 min

Case #5

Lunar Commuter Mission:
(LEO ⟶ LLO ⟶ LEO)
- 36-hr "1-way" transit times
- Passenger Transport Module (PTM) ~15.2 t; includes
- 18 passengers and 2 crew
- In-line LO_2 element ~74.5 t
- Common LH_2 NTPS ~ 70.9 t
- IMLEO ~160.6 t
- Refueled LLO_2 ~67.9 t
- Total Mission Burn Time: ~25.3 min



Commuter Shuttle with PTM

Sampling of LANTR Missions, Vehicle Types, and Refueling Needs Using Volcanic Glass and LPI as Source Material

NTR "Propelling Us to New Worlds"

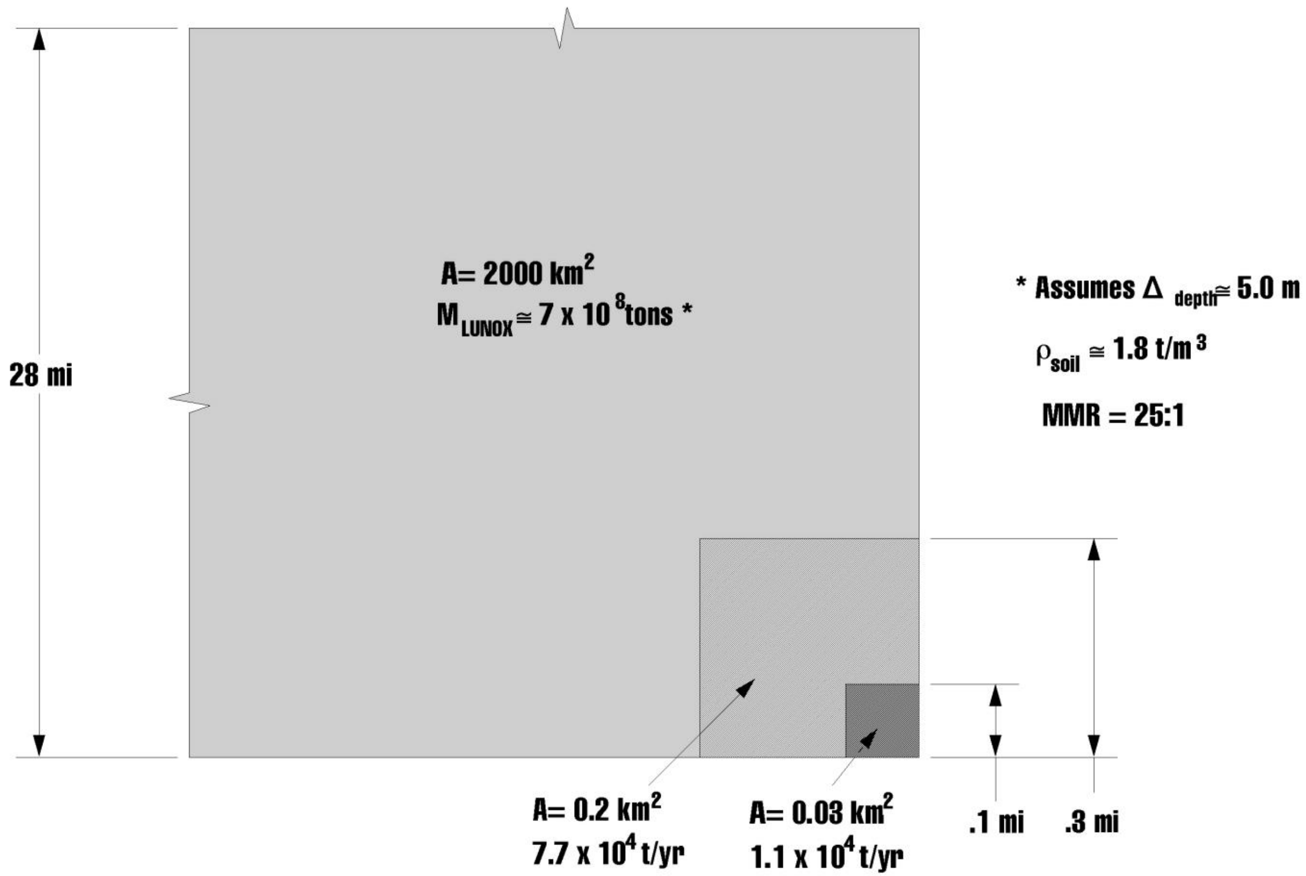
	Case Description *	Objective	Trajectory/Orbits **	In-line LO_2 Tank	Results
Crewed Cargo Transport Missions	1. Crewed LANTR LTV with MPCV and 12 m saddle truss carrying 5 t cargo to LLO	Determine LLO_2 refueling needed to deliver 5 t cargo to LLO	72 hour 1-way transit times; LEO – LLO – LEO ΔV ~7.984 km/s	7.6 m OD x ~5.23 m L (~163.5 t LO_2)	IMLEO ~ 152.4 t; ~48.8 t LO_2 supplied in LEO; ~46.9 t LLO_2 refueling in LLO
	2. Crewed space-based LANTR LTV with 9.9 t hab module and 11 m star truss carrying 5 t cargo to LLO	Determine LLO_2 refueling needed to deliver 5 t cargo to LLO using alternative LTV configuration	72 hour 1-way transit times; LEO – LLO – LEO ΔV ~7.996 km/s	4.6 m OD x ~3.4 m L (~35.9 t LO_2)	IMLEO ~ 131.1 t; ~35.9 t LO_2 supplied in LEO; ~35.1 t LLO_2 refueling in LLO
	3. Crewed space-based LANTR LTV with 9.9 t hab module and 11 m star truss carrying 5 t cargo to LLO	Determine LLO_2 refueling needed to deliver 5 t cargo to LLO while also cutting transit times to 48 hrs	48 hour 1-way transit times; LEO – LLO – LEO ΔV ~8.695 km/s	4.6 m OD x ~4.1 m L (~48.0t LO_2)	IMLEO ~ 143.4 t; ~48.0 t LO_2 supplied in LEO; ~47.0 t LLO_2 refueling in LLO
	4. Crewed space-based LANTR LTV with 9.9 t hab module and 11 m star truss carrying 5 t cargo to LLO	Determine LLO_2 refueling needed to deliver 5 t cargo to LLO while also cutting transit times to 36 hrs	36 hour 1-way transit times; LEO — LLO – LEO ΔV ~9.838 km/s	4.6 m OD x ~6.1 m L (~81.2 t LO_2)	IMLEO ~ 177.4 t; ~81.2 t LO_2 supplied in LEO; ~71.6 t LLO_2 refueling in LLO
Commuter Shuttle Missions	5. LANTR commuter shuttle carrying 15 t Passenger Transport Module (PTM) to LLO then back to LEO	Determine LLO_2 refueling needed to deliver the PTM to and from LLO with transit times of 36 hrs	36 hour 1-way transit times; LEO – LLO – LEO ΔV ~9.835 km/s	4.6 m OD x ~5.4 m L (~69.3 t LO_2)	IMLEO ~ 160.6 t; ~69.3 t LO_2 supplied in LEO; ~67.9 t LLO_2 refueling in LLO
	6. LANTR commuter shuttle carrying 15 t PTM to LPO then back to LEO	Determine LLO_2 refueling needed to deliver the PTM to and from LPO with transit times of 36 hrs	36 hour 1-way transit times; LEO – LPO – LEO ΔV ~10.006 km/s	4.6 m OD x ~6.0 m L (~80.0 t LO_2)	IMLEO ~ 172.5 t; ~80.0 t LO_2 supplied in LEO; ~72.1 t LLO_2 refueling in LLO
	7. LANTR commuter shuttle carrying 15 t PTM to LPO then back to LEO	Determine LLO_2 refueling needed to deliver the PTM to and from LPO; NTPS tops off with excess LLH_2	36 hour 1-way transit times; LEO – LPO – LEO ΔV ~10.047 km/s	4.6 m OD x ~4.6 m L (~56.4 t LO_2)	IMLEO ~148.2 t; LTV refuels with ~55.3 t LLO_2 and NTPS tops off with ~6.9 t excess LLH_2
	8. Rapid commuter shuttle carrying 15 t PTM to LPO then back to LEO	Determine feasibility of 24 hour transits using twin LANTR engines; NTPS tops off with excess LLH_2	24 hour 1-way transit times; LEO – LPO – LEO ΔV ~13.225 km/s	4.6 m OD x ~8.3 m L (~116.6 t LO_2)	IMLEO ~204.3 t; LTV refuels with ~105.6 t LLO_2 and NTPS tops off with ~13.2 t excess LLH_2

* Cases 1 – 8 use a "Common NTPS" (carries ~39.7 t LH_2); Propellant depots assumed in LEO, LLO and LPO; LANTR engines use optimized MRs

**LEO – 407 km, LLO – 300 km equatorial, LPO – 300 km polar orbit; Total round trip mission ΔV values shown include g-losses

Mining Area and LUNOX Production Rates to Support "24 Hour" Lunar Commuter Flights

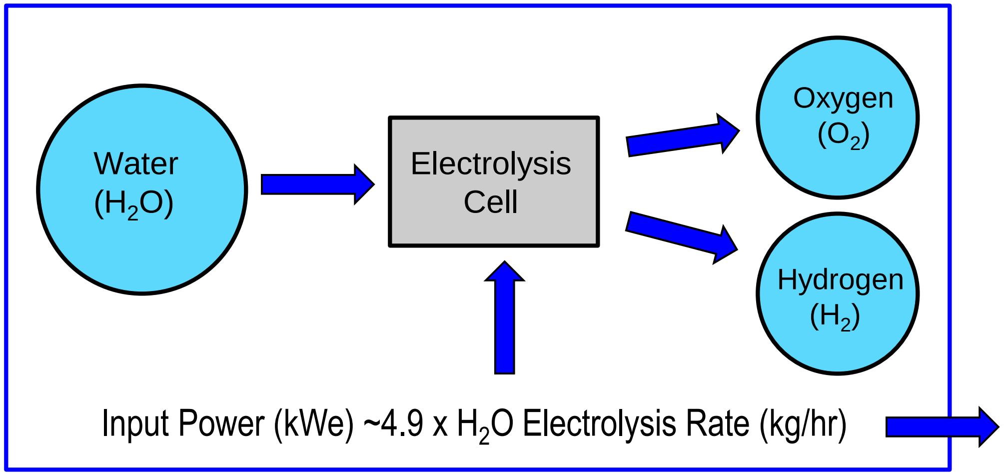
At the southeastern edge of the "Sea of Serenity" lies a vast deposit (~4000 km^2) of iron-rich volcanic glass beads tens of meters thick (one of many sites on lunar nearside)



Could supply enough LUNOX for daily 24 hour commuter flights to Moon for next 9000 yrs!

Ref: S. K. Borowski, et al., "*2001: A Space Odyssey*" Revisited – The Feasibility of 24 Hour Commuter Flights to the Moon Using NTR Propulsion with LUNOX Afterburners", AIAA-1997-2956

Power Requirements for Electrolysis of Lunar-derived H_2O to Produce LLO_2 and LLH_2 Propellants



Water Composition: $M_{H20} = M_{O2} + M_{H2}$

and for $M_{O2} / M_{H2} = 8$

$\Rightarrow$ $M_{H20} = 9 \times M_{H2} = 1.125 \times M_{O2}$

Total power requirement will include mining, beneficiation (if required), processing and H_2O formation, electrolysis and storage)

- Quantities of LDPs and required power levels will depend on mission type and frequency
- Ex: Tanker LLV (Isp = 465 s; O/H MR = 6:1) delivering H_2O to LPO depot also requires LLO_2 and LLH_2
- To produce 100 t of LO_2 (+ 12.5 t of LH_2 byproduct) on LS or depot requires electrolysis of 112.5 t H_2O
- Required Energy for Electrolysis = 112.5×10^3 kg x 4.9 kW_e- hr / kg = 5.513×10^5 kW_e- hr
- Produced over 26 weeks (4.38×10^3 hr) requires ~126 kW_e
- Produced over 1 week (168 hr) requires ~3.28 MW_e

"Propelling Us to New Worlds"

Summary and Conclusions

- NTP offers significant benefits for lunar missions and can take advantage of the leverage provided from using LDPs – *"when they become available"* – by transitioning to LANTR propulsion

- LANTR provides a variable thrust and Isp capability, shortens burn times and extends engine life, and allows bipropellant operation

- Production of LUNOX from vast volcanic glass deposits is more established (O_2 extraction efficiency, location of candidate sites and estimated quantities of source materials) than mining and extraction of H_2O from ice deposits located within deep, permanently shadowed, and extremely cold craters located at the Moon's poles. Preliminary analysis and implications of using each option have been identified

- Additional analyses & trade studies are required to better understand the pros & cons of each option

Future Work and Possible Trades

- Number of LANTR engines to use on the NTPS (also LH_2 tank size and propellant capacity)
- Size options for in-line LO_2 tank (4.6 m diameter or larger? fixed tank length or customized?)
- LDP production levels and power requirements to reach certain mission / performance levels (must consider the total requirements for both the LLVs as well as the LTS)
- Power levels required for surface production of LDPs versus that required for H_2O electrolysis at depot – Is there an identifiable split on power level for both application?
- Use of solar power versus nuclear power on lunar surface and in lunar orbit
- Use of GO_2/GH_2 RCS instead of storable bipropellant system
- Possible use of EML1 for staging node and propellant depot location